Turbo Packet Combining Techniques for Multi-Relay-Assisted Systems over Multi-Antenna Broadband Channels

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ABSTRACT

This paper focuses on turbo packet combining techniques for multi-relay-assisted systems operating over multiple-input multiple-output (MIMO) broadband channel. Two packet combining techniques are studied, signal-level packet combining and soft information-based combining. In this paper, a comparative study, in term of implementation cost and performance evaluation, is presented. Using complexity analysis and throughput simulations, we demonstrate that the choice of the best combining technique depends on the system configuration.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Wireless communication.

General Terms

Algorithms, Performance.

Keywords

Cooperative relaying, multiple-antenna systems, turbo equalization, packet combining.

1. INTRODUCTION

Relaying is an efficient technique that aims to achieve the benefits of spatial diversity with the assistance of one or more relays [1, 2]. Several interesting relaying schemes have been proposed, among which are two basic modes: amplify-and-forward (AF) and decode-and-forward (DF). Under the AF scheme, the relay amplifies the received signal and forwards it towards destination. However, in the DF scheme, the relay first decodes the signal received from the source, re-encodes and retransmits it to the destination. This approach suffers from error propagation when the relay transmits an erroneously decoded data block [2]. Selective DF scheme, where the relay transmits only when it can reliably decode the data packet, has been introduced as an effective method to reduce error propagation [3]. In this work, Selective DF scheme is considered as it is the focus of most of the next generation wireless networks standards such as IEEE 802.16j [4]. Moreover, we consider a broadband multi-relay-assisted system operating under the framework of protocol II where the source broadcasts the data packet to both the relays and the destination during the first slot, while during the relaying slots only the relay sends the packet to the destination [5]. This protocol scheme presents a generalization of automatic repeat request (ARQ) mechanisms and is widely regarded as an efficient relaying scheme for increasing the overall throughput with a very well source battery life saving.

To improve spatial diversity of a relay-assisted system, signals received over the source-destination and relay-destination links are combined at the destination side. In this paper, we focus in the study of packet combining techniques for space-time bit interleaved coded modulation (STBICM) relay systems. A variety of combining techniques have been proposed for ARQ transmissions [6, 7], among which are two famous combining schemes: signal-level packet combining (SL-PC) and log-likelihood-ratio based packet combining (LLR-PC). In SL-PC, the packet combining is performed jointly with equalization while in LLR-PC the equalization is performed separately on each transmission, and before soft input soft output (SISO) decoding, the extrinsic LLRs generated by the soft demapper are simply added to those obtained of previous transmission. To the best of the authors' knowledge, the study of this combining techniques, i.e., SL-PC and LLR-PC, under the framework of relay-assisted systems is not investigated yet, and this is the gap that this paper aspires to fill. In this work, we focus on implementation cost and performance evaluation of SL-PC and LLR-PC for

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both cooperative ARQ communications, where the feedback from the destination is exploited [8, 9], and fixed-relay communications. Throughout the paper we use the following notation: $\mathrm{diag}\{\mathbf{x}\}$ and $\mathrm{diag}\{\mathbf{X}_1, \cdots, \mathbf{X}_m\}$ denote the diagonal matrix and the block diagonal matrix constructed from $\mathbf{x} \in \mathbb{C}^n$ and from $\mathbf{X}_1, \cdots, \mathbf{X}_m \in \mathbb{C}^{n_1 \times n_2}$, respectively. $(.)^\top$ and $(.)^{\mathrm{H}}$ are the transpose and the transpose conjugate of the argument, respectively. For $\mathbf{x} \in \mathbb{C}^{TN}$, $\mathbf{x}_f$ denotes the discrete Fourier transform (DFT) of $\mathbf{x}$, i.e. $\mathbf{x}_f = \mathbf{U}_{T,N}\mathbf{x}$, with $\mathbf{U}_{T,N} = \mathbf{U}_T \otimes \mathbf{I}_N$, where $\mathbf{I}_N$ is the $N \times N$ identity matrix, $\mathbf{U}_T$ is a unitary $T \times T$ matrix whose (m, n)th element is $(\mathbf{U}_T)_{m,n} = \frac{1}{\sqrt{T}} e^{-j(2\pi mn/T)}$, $j = \sqrt{-1}$, and $\otimes$ denotes the Kronecker product.

The remainder of the paper is organized as follows: In section 2, we introduce the multi-relay-assisted system communication model. In section 3, the multi-relay conventional receiver with no packet combining is presented as a reference to evaluate the implementation cost of the studied packet combining techniques. Section 4 details the studied turbo packet combining techniques. Complexity analysis is presented in section 5. Numerical results and performance evaluation are provided in section 6. The paper is concluded in section 7.

2. RELAY SYSTEM MODEL

We consider a multi-relay-assisted wireless communication system, where the M_{S} antenna source terminal denoted as S transmits information blocks to the M_{D} antenna destination terminal denoted as D with the assistance of $K-1$ dedicated relays denoted as $\mathrm{R}_2, \cdots, \mathrm{R}_k, \cdots, \mathrm{R}_K$. Each relay R_k is equipped with M_{R_k}transmit and receive antennas. We consider a relaying system using up to K time slots for sending one information block from the source to the destination, where each slot spans T channel uses. During the first time slot, the source broadcasts the data packet to the $K-1$ relays and the destination. During the following slots, each relay participates to the packet retransmission during the allocated slot and keeps silent during the other slots. In this work, we focus on two kind of cooperative communications, fixed-relay communications and cooperative ARQ communications. In fixed-relay communication, the packet retransmission is activated during the $K-1$ relaying slots and the data packet turbo decoding, at destination side, didn't start before the last time slot K. While in cooperative ARQ, the data packet turbo decoding is performed at each time slot and the feedback from the destination is exploited. In fact in cooperative ARQ, the packet retransmission is activated only if the destination fails to decode the data packet. Therefore, during the relaying slots, once decoding is successful, the destination broadcasts a positive acknowledgment (ACK) to the source and the relays to stop relaying the current block and move on to the next information block. In this work, we suppose perfect packet error detection and assume that the one bit ACK/NACK feedback message is error-free. The source-relay ($\mathrm{S} \rightarrow \mathrm{R}_k$), source-destination ($\mathrm{S} \rightarrow \mathrm{D}$), and relay-destination ($\mathrm{R}_k \rightarrow \mathrm{D}$) links are assumed to be frequency selective. The channel matrices corresponding to the $A \rightarrow B$ link are $\mathbf{H}_0^{(AB)}, \cdots, \mathbf{H}_{L_{AB}-1}^{(AB)} \in \mathbb{C}^{M_B \times M_A}$ with L_{AB} denotes the number of symbol-spaced taps, $A \in \{\mathrm{S}, \mathrm{R}_k\}$, and $B \in \{\mathrm{R}_k, \mathrm{D}\}$. Their entries are zero-mean circularly symmetric complex Gaussian random variables. Cyclic prefix (CP)-aided transmission is assumed for all links. This prevents inter-block interference and allows us to use frequency domain processing at the receiver side. The average energies of the different links are E_{SR_k}, E_{SD} and $E_{\mathrm{R}_k\mathrm{D}}$, and take into account the path-loss and shadowing effects of each link. We suppose that no channel state information at the transmitter (CSIT) is available and assume perfect channel state information (CSI) at the relays and the destination.

First, the source encodes its data blocks using a STBICM encoder. Moreover, to have independent transmitted symbols, we suppose infinitely deep interleaving. The resulting symbol vector, at the output of the STBICM encoder, is given by,

$$\mathbf{s} \triangleq \left[\mathbf{s}_0^\top, \cdots, \mathbf{s}_{T-1}^\top\right]^\top \in \mathcal{S}^{M_S T}, \qquad (1)$$

where $\mathbf{s}_i \triangleq \left[s_{1,i}^\top, \cdots, s_{t,i}^\top, \cdots, s_{M_{\mathrm{S}},i}^\top\right]^\top \in \mathcal{S}^{M_{\mathrm{S}}}$ is the symbol vector at channel use $i = 0, \cdots, T-1$, and $\mathcal{S}$ is the symbol constellation set. During the first slot, the source inserts a CP symbol word of length $T_{CP}^{\mathrm{S}\to\mathrm{D}} \geq \max\limits_{k=2,\cdots,K} (L_{\mathrm{SR}_k}, L_{\mathrm{SD}})$, then broadcasts the resulting symbol frame. After CP deletion, the baseband $M_{\mathrm{D}} \times 1$ signal vector obtained at the destination side is given by,

$$\mathbf{y}_i^{(1)} = \sqrt{E_{\mathrm{SD}}} \sum_{l=0}^{L_{\mathrm{SD}}-1} \mathbf{H}_l^{(1)} \mathbf{s}_{(i-l) \bmod T} + \mathbf{n}_i^{(1)}, \qquad (2)$$

where $\mathbf{H}_l^{(1)} = \mathbf{H}_l^{(\mathrm{SD})}$, and $\mathbf{n}_i^{(1)} \sim \mathcal{N}\left(\mathbf{0}_{M_{\mathrm{D}} \times 1}, \sigma^2 \mathbf{I}_{M_{\mathrm{D}}}\right)$ is the thermal noise. During the following $K-1$ slots, each relay first decodes the received signal packet. If the decoding outcome is correct, the relay re-encodes the information block using the same STBICM encoder as the source, and retransmits the resulting block, i.e., the symbol block is given by (1), during the allocated slot using at most M_{S} antennas. In this case, the received signal at the destination side during slot k is expressed as

$$\mathbf{y}_i^{(k)} = \sqrt{E_k} \sum_{l=0}^{L_k-1} \mathbf{H}_l^{(k)} \mathbf{s}_{(i-l) \bmod T} + \mathbf{n}_i^{(k)}, \qquad (3)$$

where $\mathbf{H}_l^{(k)} = \mathbf{H}_l^{(\mathrm{R}_k\mathrm{D})} \in \mathbb{C}^{M_{\mathrm{D}} \times M_{\mathrm{S}}}$, $L_k = L_{\mathrm{R}_k\mathrm{D}}$, and $E_k = E_{\mathrm{R}_k\mathrm{D}}$. If the decoding outcome is erroneous, the packet retransmission is not activated during slot k. The block communication model, at transmission k, can be written as,

$$\mathbf{y}^{(k)} = \boldsymbol{\mathcal{H}}_c^{(k)} \mathbf{s} + \mathbf{n}^{(k)}, \qquad (4)$$

where $\mathbf{y}^{(k)} \triangleq \left[\mathbf{y}_0^{(k)\top}, \cdots, \mathbf{y}_{T-1}^{(k)\top}\right]^\top$, $\mathbf{n}^{(k)} = \left[\mathbf{n}_0^{(k)\top}, \cdots, \mathbf{n}_{T-1}^{(k)\top}\right]^\top$ and $\boldsymbol{\mathcal{H}}_c^{(k)} \in \mathbb{C}^{TM_{\mathrm{D}} \times TM_{\mathrm{S}}}$ is a block circulant matrix whose first $TM_{\mathrm{D}} \times M_{\mathrm{S}}$ column matrix is

$$\left[\mathbf{H}_0^{(k)\top}, \cdots, \mathbf{H}_{L_k-1}^{(k)\top}, \mathbf{0}_{M_{\mathrm{S}} \times (T-L_k)M_{\mathrm{D}}}\right]^\top. \qquad (5)$$

As $\boldsymbol{\mathcal{H}}_c^{(k)}$ is block circulant, it can be block diagonalized in a Fourier basis as $\boldsymbol{\mathcal{H}}_c^{(k)} = \mathbf{U}_{T,M_{\mathrm{D}}}^H \boldsymbol{\Lambda}^{(k)} \mathbf{U}_{T,M_{\mathrm{S}}}$, where

$$\begin{cases} \boldsymbol{\Lambda}^{(k)} \triangleq \mathrm{diag}\left\{\boldsymbol{\Lambda}_0^{(k)}, \cdots, \boldsymbol{\Lambda}_{T-1}^{(k)}\right\}, \\ \boldsymbol{\Lambda}_i^{(k)} \triangleq \sum_{l=0}^{L_k-1} \mathbf{H}_l^{(k)} e^{-j(2\pi i l/T)}. \end{cases} \qquad (6)$$

Therefore, applying the DFT on the received block signal vector (4) yields the following frequency domain block communication model,

$$\mathbf{y}_f^{(k)} = \mathbf{\Lambda}^{(k)}\mathbf{s}_f + \mathbf{n}_f^{(k)}. \tag{7}$$

3. MULTI-RELAY ASSISTED SYSTEM CONVENTIONAL RECEIVER

In this section we present a conventional receiver for multi-relay-assisted system where no packet combining is performed at the destination side. In this work, we use the conventional receiver as a reference to evaluate the implementation cost of the studied packet combining techniques. In cooperative ARQ systems, the conventional receiver performs the data packet turbo decoding during each time slot k while in fixed-relay based systems, the data packet turbo decoding didn't start before the last time slot K. First, the conventional receiver performs soft minimum mean square error (MMSE)-based turbo equalizer and computes extrinsic LLR about coded and interleaved bits using *a-priori* information. Second, the generated soft outputs are desinterleaved, and transferred to the SISO decoder for computing *a-posteriori* LLR on useful bits and extrinsic information on coded bits. After a preset number of iterations, the decision about the data packet is performed. In cooperative ARQ systems, If the packet is incorrectly decoded, a NACK message is sent to relay $k+1$ which starts the packet retransmission process. If the packet is correctly decoded, the destination broadcasts an ACK message to the source and relays to stop relaying and move on to the next data packet during the next time slot. Let $\tilde{\mathbf{s}}$ denotes the conditional estimate of $\mathbf{s}$ and $\sigma_{t,i}^2$ denotes the conditional variance of $s_{t,i}$. Remember that in fixed–relay based systems, the following data packet processing is performed just one time when $k = K$.

As presented in [10], the soft interferences cancellation and MMSE filtering can be implemented in the frequency domain using a forward and a backward filters. The MMSE estimate $\mathbf{z}_f^{(k)}$ on $\mathbf{s}_f$, at time slot k, can be expressed as,

$$\mathbf{z}_f^{(k)} = \mathbf{\Phi}^{(k)}\mathbf{y}_f^{(k)} - \mathbf{\Psi}^{(k)}\tilde{\mathbf{s}}_f, \tag{8}$$

where $\mathbf{\Phi}^{(k)} = \text{diag}\left\{\mathbf{\Phi}_0^{(k)}, \cdots, \mathbf{\Phi}_{T-1}^{(k)}\right\}$ is the forward filter given by,

$$\left\{\begin{array}{l} \mathbf{\Phi}_i^{(k)} \triangleq \frac{1}{\sigma^2}\left\{\mathbf{I}_{M_\mathrm{S}} - \mathbf{D}_i^{(k)}{\mathbf{C}_i^{(k)}}^{-1}\right\}{\mathbf{\Lambda}_i^{(k)}}^H, \\ \mathbf{C}_i^{(k)} = \sigma^2\tilde{\mathbf{\Xi}}^{-1} + \mathbf{D}_i^{(k)}, \end{array}\right. \tag{9}$$

with $\mathbf{D}_i^{(k)} = {\mathbf{\Lambda}_i^{(k)}}^H\mathbf{\Lambda}_i^{(k)}$and $\tilde{\mathbf{\Xi}}$ is an unconditional covariance matrix computed as the time average of conditional covariance matrices $\mathbf{\Xi}_i$ defined as, $\mathbf{\Xi}_i \triangleq \text{diag}\left\{\sigma_{1,i}^2, \cdots, \sigma_{M_S,i}^2\right\}$. $\mathbf{\Psi}^{(k)} = \text{diag}\left\{\mathbf{\Psi}_0^{(k)}, \cdots, \mathbf{\Psi}_{T-1}^{(k)}\right\}$ is the backward filter given by,

$$\left\{\begin{array}{l} \mathbf{\Psi}_i^{(k)} \triangleq \mathbf{\Phi}_i^{(k)}\mathbf{\Lambda}_i^{(k)} - \mathbf{\Upsilon}^{(k)}, \\ \mathbf{\Upsilon}^{(k)} = \frac{1}{T}\sum\limits_{i=0}^{T-1}\mathbf{\Phi}_i^{(k)}\mathbf{\Lambda}_i^{(k)}. \end{array}\right. \tag{10}$$

After computing (8), the inverse DFT (IDFT) is then applied to $\mathbf{z}_f^{(k)}$ to obtain the equalized time domain sequence, $\mathbf{z}^{(k)} = \mathbf{U}_{T,M_\mathrm{S}}^\mathrm{H}\mathbf{z}_f^{(k)}$. The MMSE estimate $z_{t,i}^{(k)}$ corresponding to antenna t and channel use i can be simply extracted from $\mathbf{z}^{(k)}$ as $z_{t,i}^{(k)} = \mathbf{e}_{t,i}^\mathrm{H}\mathbf{z}^{(k)}$, with $\mathbf{e}_{t,i}$ denotes the $(M_S i + t)$th vector of the canonical basis. The extrinsic LLRs values $\phi_{t,i,m}^{(e)}$ corresponding to coded and interleaved bits $b_{t,i,m}$ are given by,

$$\phi_{t,i,m}^{(e)}(k) = \log\frac{\sum\limits_{s\in\mathcal{S}_1^m}\exp\left\{-\frac{\left|z_{t,i}^{(k)} - g_{t,i}s\right|^2}{\theta_{t,i}^2} + \sum\limits_{m'\neq m}\phi_{t,i,m'}^{(a)}\lambda_{m'}\{s\}\right\}}{\sum\limits_{s\in\mathcal{S}_0^m}\exp\left\{-\frac{\left|z_{t,i}^{(k)} - g_{t,i}s\right|^2}{\theta_{t,i}^2} + \sum\limits_{m'\neq m}\phi_{t,i,m'}^{(a)}\lambda_{m'}\{s\}\right\}}, \tag{11}$$

where $g_{t,i}$ and $\theta_{t,i}$ denote, respectively, the equivalent channel gain at the output of equalizer and the residual interference variance corresponding to channel use i, and transmit antenna t. $\mathcal{S}_\beta^m$ is the set of symbols having the mth bit set to β, i.e., $\mathcal{S}_\beta^m = \{s : \lambda_m\{s\} = \beta\}$. The calculated extrinsic LLRs are then desinterleaved and fed back to the soft-input–soft-output (SISO) decoder.

4. TURBO PACKET COMBINING STRATEGIES FOR MULTI-RELAY ASSISTED SYSTEM

In this section, we describe two packet combining techniques, SL-PC and LLR-PC. In SL-PC technique, the packet combining is performed jointly with MMSE-based turbo equalization while in LLR-PC, the turbo equalization is performed separately on each transmission, and before SISO decoding, the extrinsic LLRs generated by the soft demapper are simply added to those obtained of previous slot.

4.1 Signal-level Packet Combining (SL-PC)

SL-PC technique consists in performing packet combining jointly with frequency domain equalization by considering each transmission as an additional set of virtual receive antennas [6]. All received signals and channel matrices corresponding to previous slots, $k-1, \cdots, 1$ should be stored at the receiver side. For that purpose, two variables recursively computed, $\underline{\tilde{\mathbf{y}}}_f^{(k)}$ and $\underline{\mathbf{D}}_i^{(k)}$, have been introduced in [11]. The first variable $\underline{\tilde{\mathbf{y}}}_f^{(k)}$ is introduced to store the received signals and calculated using the following recursion,

$$\left\{\begin{array}{l} \underline{\mathbf{y}}_f^{(k)} = \underline{\mathbf{y}}_f^{(k-1)} + {\mathbf{\Lambda}^{(k)}}^H\mathbf{y}_f^{(k)}, \\ \underline{\mathbf{y}}_f^{(0)} = \mathbf{0}_{TM_S\times 1}. \end{array}\right. \tag{12}$$

The second variable $\underline{\mathbf{D}}_i^{(k)}$ is used to store the channel frequency responses and calculated as,

$$\left\{\begin{array}{l} \underline{\mathbf{D}}_i^{(k)} = \underline{\mathbf{D}}_i^{(k-1)} + \mathbf{D}_i^{(k)}, \\ \underline{\mathbf{D}}_i^{(0)} = \mathbf{0}_{M_S\times M_S}. \end{array}\right. \tag{13}$$

Once the variables in (12) and (13) are updated the transmission at slot k can be discarded. This signal pre-processing is performed at each transmission in both cooperative ARQ systems and fixed-relay based systems. The joint MMSE-based turbo equalization can be implemented by a new forward and backward filters as follow,

$$\mathbf{z}_f = \mathbf{\Gamma}\underline{\mathbf{y}}_f^{(k)} - \mathbf{\Omega}\tilde{\mathbf{s}}_f, \tag{14}$$

where $\mathbf{\Gamma} = \mathrm{diag}\left\{\mathbf{\Gamma}_0, \cdots, \mathbf{\Gamma}_{T-1}\right\} \in \mathbb{C}^{TM_S \times TM_S}$, and $\mathbf{\Omega} = \mathrm{diag}\left\{\mathbf{\Omega}_0, \cdots, \mathbf{\Omega}_{T-1}\right\} \in \mathbb{C}^{TM_S \times TM_S}$ denote the multi-slot forward and backward filters, respectively, and are given by,

$$\begin{cases} \mathbf{\Gamma}_i \triangleq \frac{1}{\sigma^2}\left\{\mathbf{I}_{M_S} - \underline{\mathbf{D}}_i^{(k)}\mathbf{C}_i^{-1}\right\}, \\ \mathbf{C}_i = \sigma^2\tilde{\mathbf{\Xi}}^{-1} + \underline{\mathbf{D}}_i^{(k)}, \end{cases} \tag{15}$$

$$\begin{cases} \mathbf{\Omega}_i \triangleq \mathbf{\Gamma}_i\underline{\mathbf{D}}_i^{(k)} - \mathbf{\Upsilon}, \\ \mathbf{\Upsilon} = \frac{1}{T}\sum_{i=0}^{T-1}\mathbf{\Gamma}_i\underline{\mathbf{D}}_i^{(k)}. \end{cases} \tag{16}$$

After computing (14), the inverse DFT (IDFT) is then applied to $\mathbf{z}_f^{(k)}$ and the extrinsic LLRs is computed using (11). The output of the demapper is then desinterleaved and fed to a SISO decoder.

4.2 LLR-level Packet Combining (LLR-PC)

For LLR-PC, the MMSE-based turbo equalization and extrinsic LLRs computation are performed similarly to (8) and (11), respectively. The different retransmissions are then combined recursively as,

$$\underline{\phi}_{t,i,m}^{(e)}(k) = \underline{\phi}_{t,i,m}^{(e)}(k-1) + \phi_{t,i,m}^{(e)}(k). \tag{17}$$

The combined LLRs, i.e., $\underline{\phi}_{t,i,m}^{(e)}(k)$, are then desinterleaved and fed to a SISO decoder. Note that in the case of fixed-relay based systems, even if the whole data packet turbo decoding is not performed before the last time slot, i.e., $k = K$, the LLR-level packet combining receiver need to calculate the extrinsic LLRs values for each transmission k. Therefore, the MMSE estimate $\mathbf{z}_f^{(k)}$ as well as the extrinsic LLRs values $\phi_{t,i,m}^{(e)}$ are calculated at each transmission k.

5. COMPLEXITY EVALUATION

In this section, we briefly analyze the computational cost and memory requirements of the studied packet combining techniques for both cooperative ARQ systems and fixed-relay based systems. Compared to the conventional receiver, both packet combining techniques, presented in section 4, have identical implementation. The only difference in implementation cost comes from recursions (12), (13), and (17). In the following, we focus on the computational complexity and memory required by the packet combining recursions.

For SL-PC, the packet combining is performed with the aid of equations (12) and (13). This translates into a memory size of $2TM_{\mathrm{S}}\left(M_{\mathrm{S}}+1\right)$. For LLR-PC, a storage capacity of $TM_{\mathrm{S}}\log_2|S|$ is required to store LLR values corresponding to all transmissions. In cooperative ARQ systems, where the whole decoding process is performed at each transmission, both receivers have identical computational complexity. The only difference comes from arithmetic additions needed in packet combining recursions. Let N denotes the preset number of turbo iterations. Therefore, in the SL-PC, $2TM_{\mathrm{S}}N(k-1)\left(M_{\mathrm{S}}+1\right)$ arithmetic additions is required to update variables in (12) and (13), while in LLR-PC, $TM_{\mathrm{S}}N(k-1)\log_2|S|$ arithmetic additions is required to update variable in (17). The implementation requirements for SL-PC and LLR-PC techniques, in cooperative ARQ systems, are resumed in table 1. Note that, in cooperative ARQ, the choice of the best packet combining technique, in term of implementation cost, depends on the number of transmit antennas and the constellation length. The SL-PC seems to be more attractive for cooperative ARQ systems with small number of transmit antennas and high level modulation while the LLR-PC is more attractive for cooperative ARQ systems with large number of antennas and low level modulation. In contrast with cooperative ARQ, the studied packet combining receivers, in fixed-relay communication, do not have identical computational complexity. In fact, even if the whole turbo decoding did not start before the last relaying slot, i.e., $k = K$, a signal pre-processing is needed at each transmission to update recursive variables. In LLR-PC, the extrinsic LLRs values have to be calculated at each transmission k. This requires the calculation of the MMSE estimate $\mathbf{z}_f^{(k)}$ and the extrinsic LLRs values $\phi_{t,i,m}^{(e)}$, at each transmission k, using (8) and (11), respectively. Note that the calculation of $\mathbf{z}_f^{(k)}$ involves inversions of T matrices of size $M_{\mathrm{S}} \times M_{\mathrm{S}}$ at each transmission and has therefore a complexity in $\mathcal{O}(M_{\mathrm{S}}^3)$ for each channel use. The extrinsic information computation, performed with respect to (11), has a complexity that is exponential in $|S|$. Moreover, the update of variable in recursion (17) requires $TM_{\mathrm{S}}(K-1)\log_2|S|$ arithmetic additions. However, in SL-PC, the update of recursions (12) and (13) requires only $2TM_{\mathrm{S}}(K-1)\left(M_{\mathrm{S}}+1\right)$ arithmetic additions. Therefore, SL-PC is the most attractive technique for fixed-relay based systems.

	Memory	Arithmetic additions
SL-PC	$2TM_{\mathrm{S}}\left(M_{\mathrm{S}}+1\right)$	$2TM_{\mathrm{S}}N(k-1)\left(M_{\mathrm{S}}+1\right)$
LLR-PC	$TM_{\mathrm{S}}\log_2|S|$	$TM_{\mathrm{S}}N(k-1)\log_2|S|$

Table 1: The memory and the Arithmetic additions required, in cooperative ARQ systems, to implement SL-PC and LLR-PC.

6. PERFORMANCE EVALUATION

In this section, we evaluate the studied packet combining technique in term of throughput. In all simulations, we consider a STBICM scheme where the encoder is a 16 state convolutional code with polynomial generators $(35,23)_8$, and the modulation scheme is quadrature phase shift keying (QPSK). The length of the code frame is 2048 bits including tails, and the CP length is $T_{CP} = 3$. We use the Max-Log-MAP algorithm for SISO decoding, and the iterative MMSE receiver at the destination runs three turbo iterations. We consider multi-relay-assisted systems with one and two relays. The SNR_{SD} appearing in all figures is the S → D link signal-to-noise ratio per useful bit per receive antenna. For simplicity, we consider a homogeneous case in which the distance between the source and the relay l_{SR}, the relay and the destination l_{RD}, and the source and the destination l_{SD} are normalized as $l_{\mathrm{SR}} + l_{\mathrm{RD}} = l_{\mathrm{SD}} = 1$. We assume that all relays are at the same distance to the source, i.e. $l_{SR} = 0.3$. All links have the same frequency-selective fading channel profile, i.e., $L = 3$ equal power paths with the same path loss exponent $\kappa = 3$. The link average energy

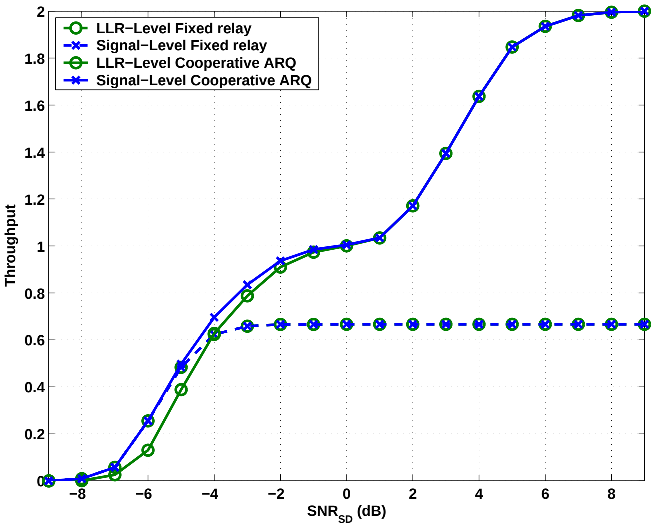

Figure 1: Throughput performance for CC $(35,23)_8$, QPSK, $M_{\rm S}=M_{\rm R}=M_{\rm D}=2$, $L=3$ equal energy paths, $l_{SR}=0.3$ and the path loss exponent $\kappa=3$.

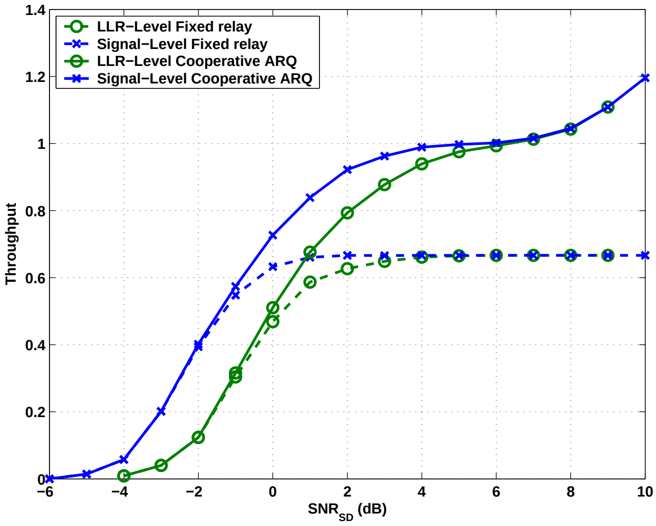

Figure 2: Throughput performance for CC $(35,23)_8$, QPSK, $M_{\rm S}=M_{\rm R}=2$, $M_{\rm D}=1$ $L=3$ equal energy paths, $l_{SR}=0.3$ and the path loss exponent $\kappa=3$.

is assumed to be $E_{AB}=(l_{AB})^{-\kappa}$ with $A=$ S or R, and $B=$ R or D. First, in Fig. 1, we consider a relaying system with the same number of transmit and receive antennas $M_{\rm S}=M_{\rm R}=M_{\rm D}=2$. We can see clearly that both combining strategies perform the same for fixed-relay based system. Therefore, SL-PC is the best choice in term of both implementation cost and throughput performance. For cooperative ARQ, we observe that SL-PC outperforms LLR-PC. However, the performance gap is insignificant. For this configuration, i.e., $M_{\rm S}=2$ and $|S|=2$, LLR-PC is the the most attractive technique in term of implementation cost with a very small loss in performance. Fig. 2 shows the performance of an overloaded system where $M_{\rm S}=M_{\rm R}=2$ and $M_{\rm D}=1$. the SL-PC technique significantly outperforms LLR-PC, i.e., the performance gap is more than 2dB for cooperative ARQ systems and 1.5dB for fixed-relay based systems.

7. CONCLUSION

In this paper, we studied two turbo packet combining techniques, i.e., SL-PC and LLR-PC, in term of both implementation cost and throughput performance. We focused on both cooperative ARQ systems and fixed-relay based systems, operating over a multiple-antenna frequency-selective channels. Using complexity analysis and throughput simulations, we have demonstrated that SL-PC is the most attractive technique for fixed-relay based systems. However, for cooperative ARQ, the choice of the best combining technique depends on the system configuration.

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